Tactical Plan for X-Ray Operations and Research at the Advanced Photon Source (2005-2015)

This Tactical Plan for X-ray Operations and Research (XOR) at the Advanced Photon Source (APS) is a companion document to the Scientific Vision for the Advanced Photon Source that addresses priorities for new or improved beamlines over the next five to ten years. Whereas the APS Scientific Vision reaches out to new communities of users and proposes new scientific directions for the APS, this plan addresses the need for dedicated facilities within X-ray Operations and Research (XOR) at the APS, and supports the new directions of the APS Scientific Vision. XOR planning has taken place in the context of the strong scientific facilities that are supported by the CAT system. In future development, the plan will explicitly join the independent CATs and XOR into a unified strategy for the APS.

Phases I and II of the APS 20-year plan, submitted to the Department of Energy in 2003, are to complete the instrumentation of the remaining beamlines and to develop optimal utilization of the source. Parallel with those developments, a reorganization of the APS has been underway over the past two years. Until recently, the sectors at the Advanced Photon Source were funded as Collaborative Access Teams, either through grants from government agencies or from industry. In 2002, DOE/BES announced that, for those sectors that BES had funded, operational funding would be transferred from the individual CATs to the APS. The gradual process of this transfer began immediately and is ongoing. Today thirteen sectors (1, 2, 3, 4, 7, 8, 9, 11, 12, 20, 26, 30, and 32) are being developed and operated wholly or in part by the APS under X-ray Operations and Research, and more are expected in the coming years. With the responsibility for a growing number of sectors, there comes a unique opportunity to enhance the capabilities of the APS facility, to create specialized beamlines, and to operate them in a manner that improves the science environment and is stable and efficient.

In August 2004, X-ray Operations and Research held an "XOR Future Directions Workshop" to gather creative input directly from the APS scientific staff. This document outlines XOR plans for developing specialized beamlines and for responding to recommendations developed at the Future Directions Workshops that were held in the summer of 2004. The focus is on providing leading edge capabilities, supporting the science at the Center for Nanoscale Materials, and reconfiguring and optimizing beamlines to ease the pressure on existing sectors. In addition, the development of new sectors is recommended, driven by scientific opportunities and the need for dedicated facilities, and assuming successful proposal processes.

As with the Scientific Vision for the APS, this document has been reviewed by the APS Scientific Advisory Council. Input on the Plan was received from the APS User Organization's Steering Committee and the APS Partner Users Council. To enable input from the entire community, we opened a web-based XOR Comment Line from May 1 – 20, 2005, where over 100 responses were received. Dialog continues to determine the most compelling first steps in its execution. This Tactical Plan is a living document,

which will guide us, but which we also expect to evolve as the science, technology and funding profile develop.

Section I presents plans for optimizing XOR and for responding to opportunities to create new world-class facilities at the APS, and Section II opens the discussion of opportunities for partnering the scientific facilities of the independent Collaborative Access Teams with XOR dedicated facilities. Three tables are given: Table A: current experimental techniques in XOR, Table B: current APS CAT facilities, and Table C: techniques in future XOR dedicated facilities.

I. X-ray Operations and Research – Dedicated facilities

Inelastic x-ray scattering

Although there was no Future Directions Workshop in inelastic x-ray scattering, the 5th International Conference on Inelastic X-ray Scattering was held at the APS in September 2004, and it served as a showcase for the latest developments in this field. Since inelastic x-ray scattering facilities are currently under construction on Sector 30, and planning for future upgrades are underway, it is appropriate that the XOR strategic plan begins here.

With brilliant x-ray sources and innovative x-ray optics, inelastic x-ray scattering (IXS) has in recent years become an increasingly valuable and even practical technique for research in geophysics, biophysics, materials science as well as fundamental science. IXS data is currently being used to determine a wide variety of material properties such as sound velocities, elastic behavior, and local atomic structure and electronic properties. Protein dynamics are being explored using density functional theory modeling constrained by IXS data, electronic structures of oxides are studied in strongly correlated electron systems in high-T_c superconductors, in colossal magnetoresistive materials, as well as in magnetic thin films and nanostructures. The community of users is large, highly successful and growing.

Facilities at 3-ID at the APS presently support the measurement of high-energy resolution (~ 1 meV) inelastic x-ray scattering (HERIX), nuclear resonant inelastic x-ray scattering (NRIXS), and Synchrotron Mössbauer Scattering (SMS). In the future, these will continue to be dedicated capabilities on sector 3, but will be utilized in different proportions than they are today. Construction of HERIX facilities at 30-ID is nearing completion, where facilities for medium energy resolution (~ 100 meV) inelastic x-ray scattering (MERIX) are following close behind. In a future upgrade, MERIX will be moved to a dedicated station of its own on 9-ID. There are two drivers for this: the community of users for both techniques is large, and the requirements from the insertion device are different for HERIX and MERIX. Placing them each on their own dedicated beamline makes it possible for us to use specialized insertion devices optimized for energy range and performance. In addition to these inelastic scattering facilities, magnetic resonant inelastic x-ray scattering (RIXS) is in commissioning on 4-ID-C, and low-

energy resolution (1 eV) inelastic scattering apparatus at 20-ID is optimized for measurement of q-dependent IXS from the core shell of low-Z atoms, providing an alternative to soft x-ray absorption spectroscopy. Resonant inelastic x-ray scattering is also done on 18-ID. Non-resonant x-ray Raman spectroscopy is done at 13-ID, 16-ID and 18-ID, and resonant inelastic x-ray scattering and x-ray Raman scattering at 16-ID and 20-ID. In addition, exact Bragg backscattering (EBB) on Sector 1 is a unique option that remains available for development. For comparison, at the ESRF there are two dedicated beamlines (ID16 and ID28) for IXS, and there are two dedicated beamlines (ID18 and ID22N) for nuclear resonant inelastic x-ray scattering. At SPring8, BL09XU is for nuclear resonant scattering and BL35XU is for high-energy-resolution inelastic scattering.

Nanomagnetism

The Workshop on Nanomagnetism using X-ray Techniques was held in August 2004 at the Abbey in Fontana, Wisconsin. A major thrust in nanomagnetism is toward understanding the magnetic behavior of the individual building blocks of matter and exploring strategies to combine them into complex structures leading to integrated systems with new functionalities. Another area is the central role played by inhomogeneities in determining collective magnetic response. In addition to the fundamental science, existing and emerging technologies are also driving today's nanomagnetism research. Fundamental scientific questions common to the technological pursuits are concerned with the origin of magnetic coupling, spin transport across interfaces, spin-lattice interactions in complex materials and the magnetic domain configuration and dynamics arising from contact between different kind of magnets.

There is a strong community of current and potential users of nanomagnetism research tools at the APS. Currently, magnetism research is carried out on 4-ID, 6-ID, 9-ID, 11-ID, 20 –ID and 33-ID. However, the only sector dedicated to magnetism-related experiments is Sector 4, where two insertion-device beamlines operate independently. 4-ID-D operates between 2.6 keV and 45 keV and 4-ID-C operates between 0.5 and 3 keV. Unfortunately, even though the quality of the facilities is good, the number of techniques supported at each beamline is too large for each of them to be optimized. For example, 4-ID-D supports magnetic diffraction, spectroscopy and imaging, where instruments for imaging and spectroscopy using the 4 T magnet must be interchanged when used. The 4-ID-C beamline supports magnetic spectroscopy, reflectivity, imaging and surface studies distributed over four separate vacuum chambers. These are again too many techniques to be efficiently supported on one beamline. The situation was recently improved with the installation of focusing optics (KB mirrors with adjustable focal lengths) so that three of the five chambers can be positioned simultaneously on the beamline. However, when either the surface magnetism or the RIXS chamber is used, one of the other chambers must be removed.

Responding to the need for dedicated tools for nanomagnetism research, and following the recommendations of the Workshop on Nanomagnetism, we propose to separate

magnetic scattering and spectroscopy by building two new insertion device beamlines: one serving the hard energy range and the other serving the soft-x-ray energy range. The new hard x-ray beamline will be optimized for resonant magnetic diffraction studies in high magnetic fields. It will make use of optimized undulators to produce a high brilliance beam, and will have two experimental stations: in an upstream station, an 8-circle diffractometer, the 4 Tesla vertical-field magnet and the 13 Tesla vertical-field magnet will be permanently placed. A downstream station can house the "big" (~ 35 Tesla vertical-field) magnet if that project is approved. The new soft-x-ray beamline will receive high intensity X rays from a new soft x-ray undulator, and will be optimized for resonant inelastic scattering, diffraction and imaging. Meanwhile, 4-ID-D will be dedicated to spectroscopy. A maximum of three chambers will be permanently installed on 4-ID-C, making use of XMCD and the 7 T field capabilities. For comparison, at the ESRF there are two soft x-ray (0.4 keV – 1.6 keV) beamlines, ID8 and ID12, for magnetic scattering. In addition, ID20 (3 keV – 20 keV) is used for magnetic studies in a high field environment, and ID24 is used for XMCD with ¼ wave plates. At SPring8, BL39XU supports magnetic scattering measurements. At the ALS, beamline 11.0.1 is used for PEEM.

Synchrotron Environmental Science

The Workshop on Future Directions in Synchrotron Environmental Science took place in May 2004 at the APS. Workshop participants made a case for the development of additional experimental stations for molecular environmental science research at the APS, primarily focused on microscale techniques, such as microprobe-XAFS. Increasing the amount of dedicated beamtime available for microprobeXAFS can be best accomplished by increasing the number of dedicated facilities.

We will make use of canted dual undulators to expand ID capabilities on sector 20. A dedicated, high efficiency microprobe XAFS station will accommodate a large number of users, including the growing community of molecular environmental science users at the APS. The other branch of 20-ID will support dedicated facilities for techniques closely related to XAFS such as x-ray Raman, DAFS, and surface XAFS. A 200 femtosecond laser at Sector 20 is used for laser pump/x-ray probe measurements. Micro-XAFS and micro-XANES are available at 20-ID, 18-ID, 13-ID, and 10-ID. For comparison, at the ESRF, ID24 (5 keV – 28 keV) is a 20-μm × 20-μm probe where one can collect XAFS spectra on the ms timescale. They also have an XAFS beamline on BM29 (4 – 74 keV).

High-energy x-ray science

The Workshop on Science with High-Energy X-rays was held at the APS in August 2004. High-energy x rays have penetration capabilities comparable to neutrons, but with better spatial resolution and considerably higher flux. High-energy x-ray research has significant impact in the areas of stress/strain measurements in engineering materials, in powder diffraction of compounds containing heavy elements, in diffuse scattering by

defects in complex oxides, in pair-distribution-function measurements of liquid and amorphous materials, and in spatially-resolved small-angle x-ray scattering from gradient layered materials. The APS is ideally suited to support high-energy x ray science in the 35 keV to 150 keV range, and has a strong track record in the development of quality hard-x-ray optics.

In both the research community and the industrial community, the number of current and potential users is large. High-energy x-ray experiments are now done at non-dedicated facilities at the APS, namely 1-ID, 5-BM, 6-ID-D, 11-ID, 13-ID, and 13-BM. Within XOR, we will dedicate 1-ID to high-energy x-ray scattering. Two undulators, one of them superconducting, will supply the high brilliance X rays. The downstream station on 1-ID will have a permanent facility for high-energy microfocusing measurements, and the upstream (10 m long) station will include SAXS, high-resolution phase-contrast imaging, powder diffraction and a 6-circle for diffraction experiments. The microfocusing capability will be capable of resolution better than 1 μm and will offer a factor of 50 – 100 improvement in flux on the sample.

In addition to the dedicated facilities on 1-ID, two stations on 11-ID will also be dedicated to high-energy x-ray research. The wiggler insertion device that currently serves 11-ID will be replaced with a pair of canted undulators, enabling11-ID-B and 11-ID-C to be dedicated to high-energy x-ray experiments requiring high x-ray flux. Techniques will include high-resolution powder diffraction, lower resolution powder diffraction for time-resolved studies, diffuse scattering, and pair distribution function measurements.

With these insertion device, optics and hutch upgrades, the APS will have four dedicated stations on two beamlines for world-class high-energy x-ray experimentation. These facilities will be unique in the United States and will be competitive with the best in the world. For comparison, facilities at the ESRF include ID11 (7 keV – 100 keV) for diffraction experiments in materials science, ID15 (40 keV – 300 keV), where there are three stations including one using a white beam, ID27 for high pressure work, and ID31 (5 keV – 60 keV) for high resolution powder diffraction and peak-shape analysis. SPring8 has BL04B2 for high-energy x-ray diffraction, and BL40XU for experiments requiring high flux.

X-ray diffraction

X-ray diffraction is a premier technique for gaining an understanding of electronic, magnetic, orbital, and structural phase diagrams as a function of thermodynamic variables such as temperature, pressure, and magnetic field. These phases may involve competition of charge order to superconducting ground states in cuprates, metamagnetic structures and multipolar ordering in rare-earth intermetallic compounds, interplay of charge, orbital, and polaronic order in oxides, magnetic field-induced structural transitions in magnetocaloric materials, or electric polarization in ferroelectrics, to cite a few examples. Transitions among various ordered phases often involve subtle changes in

atomic displacements, modulation vectors, lattice distortions, and spin anisotropy, depending on the physical system. To develop a detailed picture of the microscopic nature of such changes it is imperative to study materials in the form of single crystal and epitaxial thin films using diffraction techniques. Diffraction based techniques provide invaluable bulk structural information on long-range and short-range ordered phases of materials.

Diffraction techniques include general diffraction, diffuse scattering, magnetic scattering, grazing incidence diffraction, liquid surface diffraction, and low-energy (2.5 – 5 keV) diffraction. Each of these techniques requires the use of an appropriate goniometer for precise alignment of single crystals and epitaxial films, optics for harmonic rejection, focusing capability and energy tunability. Often these measurements are carried out as a function of temperature with the sample inside a cryostat. Depending on the system, the samples are subject to pressure, or they are placed in a magnetic or an electric field, or they are grown *in situ*.

Currently, diffraction-based techniques are available on many beamlines at the APS, including: 1-BM, 1-ID-C, 2-BM, 4-ID-D, 6-ID, 7-ID, 9-ID, 11-ID-D, 12-BM, 13-BM, 15-ID, 20-BM, 20-ID-C, 33-BM, and 33-ID. In the future, a Newport diffractometer will be permanently installed in 33-ID, with a pass-through mode for experiments in the surface-diffraction end station. A dedicated Huber diffractometer will be located at 33-BM. As future sectors come under the responsibility of XOR, the plan is to dedicate an additional permanently installed diffractometer on an ID and another on a bending magnet line. Diffraction with samples in magnetic fields are currently performed on 4-ID-D; two cryogen-free 4 Tesla magnets (horizontal and vertical) and one 13 T vertical-field magnet are available. Low energy diffraction is available on 4-ID-D and 6-ID. As indicated in the section on nanomagnetism, we anticipate that the magnetic diffraction experiments will ultimately be dedicated on new beamlines optimized for magnetic scattering. For comparison several beamlines at ESRF provide single-crystal diffraction capabilities for materials science research: ID1, BM1, BM2, BM8, ID10, ID11, ID20, BM25, and BM28. At SPring8 BL02B1, BL14B1, BL39XU, and BL46XU support single-crystal diffraction.

X-ray micro/nanodiffraction

X-ray micro/nanodiffraction is used for spatially resolved studies of crystallographic phases, phase concentrations, micro/nanostructures, stress/strain fields, and superlattice structures *via* direct probing the reciprocal lattices. Employing the weak coupling between the scattering from the principal lattice and that from the electronic states near the Fermi surface, micro/nanodiffraction can also be used to map domains of long-wavelength modulations of electronic spin density and charge density. Recently diffraction studies of internal structures of individual nanoscale materials have been carried out using X-ray beams of high flux density created with advanced micro-focusing optics.

Micro/nanodiffraction is key to understand many aspects of materials: *e.g.*, the dependence of material properties such as transport and susceptibility to their micro/nanostructures; lattice strains and deformation under external stress, and the initiation of material failure; microstructures of metal oxide films, high T_c superconducting films, and the films of giant magnetoresistance and colossal magnetoresistance; defects and dislocations in functional micro/nanomaterials and devices; structural response of epitaxial thin films to defects of substrates; polarization switching and fatigue development of ferroelectric domains; effects of the micro patterning on the mechanical stability of the microelectronic circuits; the dependencies of the nanostructure on material dimensions and growth conditions; and the roles of the domain walls of electronic spin modulations in various hysteresis behaviors in antiferromagnetic solids. Micro/nanodiffraction has broad impact on research in materials science, materials engineering, microelectronics, and condensed matter physics, and will be critically important for emerging nanoscale science and technology.

At the APS, several beamlines support micro/nanodiffraction. At 2-ID-D, a 6-circle diffractometer is integrated with a zone plate microprobe and high precision scanning stages. The facility provides flexible sample environment, such as low temperature or ultra-high vacuum. Microdiffraction with spatial resolution of 0.4 – 1 μm is also performed with white and monochromatic beams at 7-ID using ZP and KB optics. 34-ID-E has a polychromatic microdiffraction facility dedicated to measuring deformation microstructure, strain distribution, grain orientation, and dislocations in poly- and single-crystalline materials. In the future, the CNM nanoprobe at 26-ID will support nanodiffraction by means of a 30-nm probe with a single sample rotation axis, providing limited access to reciprocal space.

Powder Diffraction

Definitive knowledge of the crystal structure of a material—inorganic, organic, or biological—is the gateway to understanding its physical properties, its chemical reactivity, and/or its biological functionality. The increasingly complex chemistry and physics of modern materials demands that this structural information be obtained in a routine fashion and with state-of-the-art precision. This is true for materials of interest to fundamental physics, materials science, mineralogy, chemistry and biology. Because most of these materials only exist as polycrystalline solids, the definitive structural experiment requires high-resolution x-ray powder diffraction. Powder diffraction provides the crucial tool for determining structure, for following structural changes parametrically (temperature, field, etc.), and for defining future synthetic approaches for enhancement of some desired property (conductivity, thermal expansion, biological activity, etc.). Many of the most compelling materials that are studied today are not available in single-crystal form during the critical period following initial discovery. It is precisely during this phase that structural information is most essential. The fields of study are broad, ranging from condensed matter physics to materials chemistry and from proteins and pharmaceuticals to geoscience.

Although there was no Future Directions Workshop dedicated to powder diffraction, it was a significant part of the Workshops on Science with High-Energy X-rays and Emerging Areas in Biological Crystallography and is recognized as a creative and productive use of synchrotron radiation. At the APS, a new dedicated high resolution and high throughput powder diffractometer is nearing completion on beam line 11-BM. This instrument will be easily tunable between 4.8 keV and 40 keV, and will operate either in a high-resolution mode with a multidetector-analyser system or in a high throughput mode with a 2D imaging detector. In addition, high-energy x-ray powder diffraction capabilities will continue to be available within XOR on 1-ID and 11-ID. Also at APS, powder diffraction is available at 5-BM, 5-ID, 6-ID, 13-ID, 13-BM, 16-ID, and 33-BM. Non-XOR sectors that do powder crystallography include: 5-BM, 5-ID, 6-ID, 16-ID and 33-BM. For comparison, many synchrotron facilities have dedicated powder diffraction facilities available to general users. NSLS has three dedicated powder diffractometers (X3B1, X7A and X7B) each covering different aspects of the experimental possibilities, and has an excellent powder diffraction user program. A similar suite of instrumentation is available at ESRF encompassing both bending magnet (e.g. BM01A and B) and insertion device beam lines (ID11 and ID31). These are some of the most heavily subscribed instruments at these facilities.

X-ray absorption fine structure (XAFS)

X-ray absorption fine structure (XAFS) spectroscopy probes the physical and chemical structure of matter on an atomic scale, and it is element-specific as it measures the partial pair distribution or local structure surrounding the selected atoms. Synchrotron based XAFS has a broad user base and spans many fields, including physics, chemistry, biology, botany, geology, astronomy, physiology and toxicology. Two complementary XAFS regimes are extended x-ray absorption fine-structure (EXAFS), which provides local structural information in the vicinity of a selected probe atom, and x-ray absorption near-edge spectroscopy (XANES), which provides chemical and valence information for the selected atom. It is a technique of choice for studying atomic structure in inhomogeneous and disordered systems, including amorphous solids, ions in molecules and solutions, atomic species on surfaces, and concentrated in plant and animal cells. XAFS is uniquely suited to studying inter-atomic distances in nanoparticles below 2 nm, where finite-size broadening dominates the diffraction peak widths.

With a concentration of leaders in the XAFS field, the APS is poised to become a premier XAFS facility. All XAFS techniques share the requirement of a highly stable, continuously tunable source with energy resolution $\Delta E/E$ in the range 10^{-4} to 10^{-5}. Samples smaller than around 25×25 μm, or with concentrations of the element of interest below 10 ppm, typically require the higher brilliance provided by the APS undulators. Larger and more concentrated samples are generally considered "bulk XAFS", and are well matched to the performance of the APS bending magnets. The plan for XAFS at the XOR ID lines has been considered separately in other sections of this plan: *e.g.*, the microprobe on 20-ID and time resolved experiments on 11-ID and 20-ID include XAFS. Improvements at XOR XAFS facilities will include better detectors to

enable the measurement of XAFS at environmentally or biologically relevant concentrations. The XOR bending magnet beam lines will be optimized so that there is overlap of capabilities with regard to energy range. The inclusion of focusing optics on all XAFS bending magnet lines will yield a large improvement in performance. Standardization of XAFS data collection and on-line analysis software at all APS beamlines will significantly improve user efficiency and enhance the overall user experience at APS. Finally, standardized sample mounting strategy, particularly for different sample environments—UHV, LN2, microprobe, furnace, etc.—will further improve efficiency.

Currently, the following bending magnet beamlines support EXAFS: 5-BM-D, 9-BM-B (dedicated to XAFS), 12-BM, 13-BM, and 20-BM (dedicated to XAFS, DAFS and diffraction). The following insertion device beamlines support XAFS: 10-ID (XAFS, DAFS and μXAFS), 11-ID-D (XAFS and diffraction), 13-ID, 16-ID-B, 18-ID, and 20-ID. In the future, the 20-ID beamline will have a dedicated μ-probe XAFS line, an independent line for DAFS, x-ray Raman and surface XAFS, and high efficiency laser pump/x-ray probe time-resolved XAFS.

Time-domain science

A workshop on Time Domain Science using x-ray techniques was held in August 2004 at the Abbey in Fontana, Wisconsin where the emphasis was on synchrotron techniques for observing dynamic systems evolving or transforming *in situ*. Time-domain synchrotron x-ray research has contributed greatly to our understanding of structural changes on the ~ 100 picosecond and longer time scale and on the atomic length scale. Current time-domain research at the APS in atomic and molecular physics in the hard x-ray regime focuses on understanding strong-field effects on inner-shell processes and on monitoring Coulomb explosion dynamics. Strong AC fields, ≥ 3V/Å, are generated by means of standard ultrafast lasers. Understanding the accompanying perturbations by means of absorption and emission spectra is important for the interpretation of optical pump/x-ray probe experiments, particularly those planned for next generation light sources. Also on these time scales, the further development of macromolecular crystallography to a broader range of chemical and biological systems can be envisioned, as well as time resolved structural studies of molecular excited states and reaction intermediate structures and structural intermediates in catalytical processes and enzymatic reactions.

Time-resolved research at the APS is done on 14-ID at BioCARS, which has a pump-probe facility that makes use of pink beam for nanosecond laser pump / x-ray probe measurements. Beamline 15-ID at ChemMatCARS makes use of a nanosecond laser for time-resolved single crystal crystallography research. Facilities on XOR beamline 7-ID include a femtosecond laser, where measurements can be made with x-ray beam sizes on the submicron-scale, and time-resolved diffraction measurements with picosecond resolution. 7-ID-B supports time-resolved white/pink beam scattering and imaging; 7-ID-C supports time-resolved microbeam scattering; and 7-ID-D is dedicated to the laser-pump/x-ray probe experiments. We note that, with current operating modes, 70% of the

beam time must be allocated to experiments that do not use the bunch structure, underlining the importance of developing x-ray choppers to isolate pulses from the pulse train. With the planned development of an appropriate x-ray chopper, most of the 24-bunch mode can be used. Other time-resolved experiments (scattering and imaging) in ns-ms will coexist on this sector.

The mission of 8-ID is to develop coherent x-ray photon correlation spectroscopy, XPCS, techniques for condensed matter research. There are two independently operated end stations: 8ID-I is dedicated to XPCS in the small angle scattering regime with monochromatic or pink beam in either the transmission or reflection geometry. 8ID-E is a side branch supporting grazing incidence time-resolved small-angle x-ray scattering and x-ray micro-/nano-diffraction.

Time resolved research is also currently done on a wiggler beamline at APS Sector 11, where there is a laser with a picosecond pulse width for spectroscopy on a picosecond to microsecond time scale using special timing modes. This time-resolved science will continue to be supported on a dedicated beamline on 11-ID, after the wiggler is replaced with a pair of canted undulators. One of the undulators will enable research that includes time-resolved x-ray absorption for the investigation of nanoparticle structures, metalloprotein structures and laser induced structural changes in materials. Other areas are the molecular structures of intermediate species in photochemical and photo-physical processes using time-resolved x-ray absorption, diffraction with single laser pulse pump and single x-ray pulse probe; x- ray and optical polarization dependence of the molecules in different media; photoinduced structural changes in biological, chemical and physical process; surface structures of nanoparticles.

Thus, XOR beamlines on 7-ID, 8-ID and 11-ID will be dedicated to time resolved research. Future opportunities include the development of a high-repetition-rate, high-flux, short-pulse capability in the ps range that would be complementary (and in many cases preferable) to x-ray FEL and ERL sources. In support of these activities, we will select optimized insertion devices, x-ray optics and end stations for time-resolved beamlines, and perform the necessary development of advanced chopper designs, mirrors, and time-resolved detectors (fast readout 2D detectors, streak cameras, and avalanche photodiodes). At XOR Sector 20, there is a ps-pulse-width laser with high-rep rate at the ring frequency so as to utilize all the radiation from a single x-ray pulse for XAFS with 100 ps resolution. The resulting lower power per laser pulse is compensated by focusing to tens of microns. This activity shares a beamline with dedicated DAFS, x-ray Raman and surface XAFS. At the ESRF, time-resolved research is carried out on ID9B, which makes use of a high-speed chopper. Beamline 5.3.1 at the ALS uses a bending magnet source for subpicosecond time-resolved x-ray diffraction and absorption.

X-ray imaging

A Workshop on Emerging Scientific Opportunities using X-ray Imaging was held in August 2004 at the Abbey in Fontana, Wisconsin. X-ray imaging is key to the

investigation of structures from nanometers to centimetres to address issues such as fracture mechanics of composites and biological materials, materials microstructure/properties research including deformation and sintering, bone and cartilage growth and formation, small animal and soft tissue research on vascular networks and pulmonary ventilation, the internal structures of micro-devices, electronic components and packaging, characterization of geological structures and microfossils, cement mortar research, structure and development of foams, granular packing of non-equilibrium systems. Additional areas where x-ray imaging is expected to have significant impact in the future include: porosity distribution in foods, structure and development of seeds, subcellular organelle structures in frozen-hydrated biological cells, self-orientation on nanotemplates or in molecular beams, 3D nanocrystallites, nanoclusters and other nanostructures, and complex fluidics.

X-ray imaging at the APS includes soft x-ray scanning microscopy and soft x-ray coherent scattering, microdiffraction and diffraction imaging and topography, microtomography, radiography and phase contrast imaging, and scanning fluorescence and full-field transmission, as well as coherent diffraction imaging. These techniques are spread over 12 BES-supported beamlines, and most of the activities are not dedicated. Other beamlines support imaging as well, such as microtomography at 5-BM and scanning microprobe imaging at sector 13. Over the next few years, XOR imaging activities will be on dedicated beamlines. Beginning with sector 2, 2-BM-B will be dedicated to high throughput microtomography. 2-ID-B currently supports scanning transmission and fluorescence microscopy in the 1 keV – 4 keV range, and also supports soft-x-ray coherent scattering. We propose that this activity, along with soft-x-ray coherent diffraction and ARPES be placed in the future on a new, dedicated ID beamline. Scanning fluorescence microscopy is done on 2-ID-D (2 – 32 keV) and 2-ID-E (8 – 12.5 keV). These capabilities will eventually become dedicated on 2-ID. A dedicated station for x-ray topography currently exists on 33-BM, where a large parallel x-ray beam (8 mm × 100 mm) is used for electronic substrate and to a dedicated facility for thin film epitaxial layer research. In response to the need for facilities dedicated to full-field imaging, and in line with recommendations from the Imaging Workshop, we propose to develop a dedicated insertion device beamline on sector 32 for full-field phase contrast imaging, topography, tomography, USAXS imaging and coherent diffraction. Scanning microscopy with a 100 nm probe for micro-XAFS will be dedicated on 20-ID, as indicated above. Hard x-ray scanning microscopy for materials science with a 30 nm probe will take place on the nanoprobe beamline, currently under construction on 26-ID. With the addition of another undulator, 34-ID will support a dedicated hard-x-ray microscope and dedicated coherent diffraction imaging on two independent beamlines. Finally, there is a letter of intent for the construction of a new bionanoprobe that would be complementary to the nanoprobe for materials science, dedicated to 20 nm scanning of biological specimens.

For comparison, at the ESRF ID17 serves biomedical (angiography, therapy, etc.), ID19 (6 keV – 120 keV) is a 145-m line with a highly coherent beam (0.1 mm source size) for topography, absorption and phase contrast imaging, high-resolution diffraction. ID21 has a scanning x-ray microscope (STXM) and a full-field imaging microscope (TXM). ID22

supports microfluorescence, imaging and diffraction, and ID18F (6 keV – 28 keV) is used for micro and trace analysis. At SPring8, there is one station for microdiffraction, 2.5 stations dedicated to imaging and one station for hard microscopy. At the ALS, there is one station for microdiffraction, one for hard x-ray microscopy and three for soft x-ray microscopy. Elettra has one station for hard x-ray microscopy and one for soft x-ray microscopy. Finally, the SLS has 1.5 stations dedicated to imaging.

Small-angle x-ray scattering and ultra-small-angle x-ray scattering

Small angle x-ray scattering has been widely used to address structure characterization on a nanometer length scale (1 nm – 300 nm). With brilliant 3rd generation synchrotron x-ray sources, such studies can now be made very rapidly or on many decades in length scale. Research using small-angle x-ray scattering includes real time *in situ* investigations of biological structures such as the kinetics of proteins and RNA folding, crystallization and other self-assembling systems. SAXS studies are fundamental to understand the structures of materials such as colloidal solutions, molecular solutions, liquid crystals, glassy structures, semi-amorphous films with columnar structures, thin films, nanocrystalline materials, single crystals with defects, precipitates in metallic alloys, microcracks in fatigued materials, bubbles in sputtered films, porous materials such as aerogels, porous silicon and zeolites, polymers, biological membranes, fibres, etc.

By performing measurements in the grazing incidence geometry, one can change the penetration depth of the x-rays, making it possible to gain depth-resolved information typically between 10 nm and 200 nm. Examples of research are: surface and interface roughness of thin films and layered structures, morphology and structure of thin films on substrates, semiconductor nanostructures, quantum dots and quantum wires, shape, strain, ordering and correlation of small crystalline islands on substrates, phase transitions in thin layers, phase transitions and structures in confined environments.

Not available for real time research, but covering an exceptionally broad microstructural size range, ultra-small-angle x-ray scattering measures structures from nm to μm. It is particularly valuable where absolute calibration is required and for its ability to measure anomalous scattering even in the presence of copious fluorescence from other elements in the beam.

At the APS, 7 beamlines (1-ID, 5-ID, 9-ID, 12-ID, 15-ID, 18-ID, and 33-ID) currently support small angle x-ray scattering, but none of them is dedicated. Within XOR, high-energy small angle x-ray scattering will continue to be done on 1-ID, grazing incidence SAXS on 1-BM and 8-ID, and SAXS on 8-ID, 9-ID and 12-ID. Soon expected to join XOR, 33-ID currently supports USAXS. Within XOR, we will move 9-ID SAXS activities to 12-ID, where the SAXS instrument will become dedicated. With the installation of a second undulator in Sector 12, the USAXS will be on a separate dedicated line. The grazing geometry instruments will be dedicated on 1-BM and 8-ID. Outside XOR, SAXS is supported at the APS at 5-ID, 15-ID and 18-ID.

Surface and interface scattering

Knowledge of atomic structural arrangements and chemistry at surfaces and buried interfaces provides important insight into the function and properties of man-made structures and of natural processes. X rays offer a unique opportunity to penetrate through gas, liquid, or solid thin-film overlayers to probe the structure and chemistry of surfaces and internal boundaries on the atomic length scale. The brilliance of the APS enables *in-situ* studies, and permits real-time investigations to elucidate thin film growth mechanisms as well as chemical interactions at surfaces and internal boundaries.

Using techniques such as surface/interface diffraction, truncation rod scattering, reflectivity, and standing wave measurements, synchrotron science has impacted many areas including environmental and geochemical sciences, condensed matter physics, semiconductor technologies, energy technologies (such as photovoltaics, fuel cells and superconductivity), photonics, chemistry, and nanoscale science and technology. Many of these techniques have been developed independently at APS sectors so that currently this research activity is found at the following beam lines: 5-ID, 6-ID, 7-ID, 11-ID, 11-BM, 12-ID, 13-ID, 20-ID, 33-ID, and 34-ID. As part of this plan, consolidation of many of the activities in surface and interface science will bring effective and efficient access to investigators at the forefront in many disciplines, and will free beam time at other sectors to enable those to better optimize in other research areas.

Incorporated into one sector will be thin film growth capabilities (such as MOCVD, MBE, PLD, etc), as well as the facilities to enable electrochemical, oxidation and geo-chemical surface and interface studies. These are studies that sometimes require specialized diffractometers or UHV chambers and sometimes specialized environmental chambers that mount to standard scattering goniometers. Often, these experiments require complex and time-consuming preparations such as chamber bake-out, or establishment of deposition growth conditions. Through the use of canted undulators, it will be possible to have two ID lines dedicated to surface/interface scattering at a single sector. Since many of the experiments can be performed at fixed, relatively high energy (*e.g.* 30 keV), the use of single-crystal monochromators to separate one of the undulator beams from the other, and allow simultaneous operation and beam switching (rather than moving of large endstation equipment) makes this research area ideal for a canted undulator sector where as many as four surface/interface experiments can operate simultaneously.

So that the scientific and technical needs for these capabilities can be fully understood, and the APS positioned to exploit new opportunities in these areas, a workshop is planned for September 2005. Recommendations that emerge from the workshop will help direct decisions regarding how an existing sector (such as sector 33) could be reconfigured to serve this community, or whether a green field facility might be required. In addition, efforts will be made to exploit the synergy between advanced x-ray surface and interface techniques and the users and capabilities of the Center for Nanoscale Materials.

For comparison, at the ESRF, ID1 (2 keV – 42 keV) has an undulator and a wiggler on a low-beta section and supports grazing incidence diffraction, GISAXS and anomalous x-ray diffraction. ID3 (5 keV – 25 keV) supports surface diffraction with a UHV diffractometer including MBE, and another diffractometer for horizontal surfaces, XSW and XPS. ID32 (2.5 keV – 40 keV) supports surface x-ray diffraction, XSW and XPS. SPring8 has BL13XU for surface studies.

Nanomaterials science

X-ray tools for nanomaterials science enable the quantitative analysis of compositional, structural, chemical, magnetic and dynamic properties at the interatomic, atomic and molecular level, over a wide range of time scales, and including *in-situ* capabilities. The Center for Nanoscale Materials (CNM), currently under construction in partnership with the APS at sector 26, will be dedicated to the development and characterization of novel materials and devices at the nano-scale.

The CNM Hard X-ray Nanoprobe Facility will provide unique hard x-ray microscopy capabilities dedicated to the study of nanoscale materials and devices. The Nanoprobe will provide analytical capabilities at a spatial resolution of 30 nm, and provide fluorescence spectroscopy, diffraction imaging and microdiffraction and high-resolution transmission imaging. It will provide tunable, circularly polarized x-rays for the study of magnetic materials, and provide capabilities for time-resolved studies. The CNM will provide complementary characterization tools in its adjacent building including scanning probe and electron microscopy.

In addition to the Nanoprobe instrument, the APS provides numerous complementary experimental facilities that serve the community of nanoscience researchers in the areas of interfacial structures, nano-systems, confinement, and self-assembly of hard materials, soft materials, and biomaterials, or nanofluidic phenomena. These facilities include several nanoprobes around the APS ring:

- x-ray-excited optical luminescence (XEOL)
- soft-x-ray photoelectron emission spectroscopy (PEEM)
- (6 – 13 keV) scanning fluorescence microscopy and micro/nano-diffraction (70 nm probe)
- (1 keV – 4 keV) scanning transmission microscopy, scanning fluorescence microscopy, and coherent scattering (50 nm probe)

In addition to these imaging techniques, x-ray scattering provides another important approach to the study of nanoscale materials. Capabilities at the APS include:

- Characterization of magnetic interfaces using magnetic reflectivity

- Small-angle X-ray scattering and grazing incidence small-angle x-ray scattering for following, in situ and in real time, the formation of nanocrystal monolayers, nanoparticle arrays and the associated kinetics
- Coherent diffraction, currently under development at the APS and sometimes called "lensless imaging," for imaging structures at the nanoscale
- Diffraction under *in-situ* growth, including MBE, MOCVD, and PLD
- X-ray photon correlated spectroscopy (XPCS)

II. Partnering the scientific facilities of the independent Collaborative Access Teams with XOR dedicated facilities

This section highlights unique capabilities of the CATs and begins the process of integrating these with those of X-ray Operations and Research into a unified strategy for the APS. Research capabilities of the CATs are outlined and opportunities for partnering are delineated.

Sector 5 DND-CAT

The scientific thrusts of DND-CAT are concentrated in three main areas: 1) studies of atomic structures at surfaces, interfaces and thin films, using techniques such as surface diffraction and x-ray standing waves both in UHV and non-UHV environments; 2) studies of catalysis, using in-situ EXAFS and powder diffraction; and 3) studies of polymer science (described more in detail below). The CAT also supports smaller user groups pursuing research in macromolecular crystallography, environmental science, and high-energy diffraction applied to problems in materials science.

The emphasis on polymer science is unique at the APS, and includes ultra-low-background pinhole-camera SAXS to study large scale structure, simultaneous SAXS and wide-angle time-resolved techniques to study crystallization and melting, and microtomography to investigate internal damage. The CAT also has ancillary equipment such as an Instron servo-hydraulic system for deformation studies, and a custom DSC cell for temperature dependent studies. DND-CAT provides an important resource at the APS for new users in the polymer field.

Sector 6 MU-CAT

The Midwest Universities Collaborative Access Team supports a diverse array of research in four main areas: magnetic scattering, surface scattering, local structure determination, and general scattering and spectroscopy. MU-CAT has made and

continues to make significant contributions to the APS community through x-ray diffraction and the other areas it supports.

Sector 10 MR-CAT

Scientific programs at MR-CAT include micro-XANES and micro-XAFS and fluorescence imaging for research in materials science, condensed-matter physics, and environmental geoscience. With these tools, important *in-situ* studies are carried out on systems ranging from fuel cells to catalysts on carbon nanotubes to biometals and biomineralization. MR-CAT serves a number of communities and is particularly strong in spectroscopy requiring high-brightness collimated beams and microbeam studies in materials and environmental science. The development of LIGA x-ray lithography on 10-BM is unique at the APS.

Sector 13 GSE-CARS

GeoSoilEnviroCARS strives to be the foremost facility in the world for earth, planetary and environmental science research using synchrotron radiation. It supports research on the composition, structure and properties of earth and planetary materials, the processes they control and the processes that produce them. Experiments include high-pressure research, x-ray diffraction and scattering, x-ray absorption spectroscopy, x-ray fluorescence microprobe analysis, microtomography and inelastic scattering, frequently involving specialized sample environments. Among the unique capabilities are a 1000 ton multi-anvil press on the ID beamline, Brillouin scattering system on the bending magnet beamline, and large Kirkpatrick-Baez mirrors coupled to a high-performance Newport diffractrometer on the ID beamline.

Sector 15 ChemMatCARS

ChemMatCARS is a synchrotron resource supported by the National Science Foundation and Department of Energy dedicated to chemistry and materials science. The scientific program is centered on aspects of dynamic and structural condensed matter and materials chemistry. Scientific areas include: surfaces and interfaces in soft condensed matter and molecular liquids, chemical crystallography, structure of molecular aggregates and semiconductors, structures of novel composites, metalloproteins and enzymes. Beamtime is allocated to the community via the APS General User proposal review system.

Sector 16 HP-CAT

HP-CAT adds the dimension of pressure to a number of synchrotron x-ray diffraction and x-ray spectroscopy probes in its well-equipped sector. The facilities are optimized for

high pressure and high/low temperature measurements using small-focal-spot size and high-energy x rays. Future developments in partnership with the APS may include the development and installation of improved focusing mirror optics and the important addition of a short-period undulator. To maximize the impact of the pressure dimension to physical, chemical, geological, and biological sciences, HP-CAT collaborates in the development and incorporation of high-pressure experimentations with other specialized nanofocusing, high-energy, high-resolution, and high-brilliance sectors. Future development of large single-crystal CVD diamond for anvils holds the promise of future studies in environments up to 10,000 K and many megabar.

Sector 18 Bio-CAT

The Biophysics Collaborative Access Team supports research into the structure of partially ordered biological molecules, complexes of biomolecules, and cellular structures under conditions similar to those found in living cells. Techniques include time- and spatially-resolved small-angle x-ray scattering, x-ray diffraction and x-ray absorption/emission spectroscopy, where these are complementary to macromolecular crystallography. Of key importance is the infrastructure relevant to biology that this CAT brings to the APS in this unique facility.

Biological crystallography at the APS

The facilities at BioCARS (sector 14), IMCA-CAT (sector 17), SBC-CAT (sector 19), SER-CAT (sector 22), NE-CAT (8-BM), DND-CAT (5-ID), and SGX-CAT (sector 31)–and in the future LS-CAT (sector 21), GM/CA-CAT (sector 23), and NE-CAT (sector 24)–at the APS offer to the biology community an outstanding portfolio of biological crystallography capabilities. Synchrotron radiation has made a remarkable impact on macromolecular crystallography in that most structures are now solved at synchrotron sources, where the tunability and intensity of the radiation has enabled the development of anomalous dispersion techniques for structure solution. Biological crystallography capabilities at the APS include single crystal diffraction, measurement of macromolecular assemblies, membrane protein crystallography, time-resolved crystallography, atomic resolution crystallography, Laue diffraction and powder diffraction. XOR, together with the biological community, has designed and commissioned a new cryogenic crystal-mounting robot, and canted undulators are enabling additional measurement capacity. Also of great importance is the realization of simultaneous measurement capabilities to integrate x-ray techniques with other methods, and the development of a dedicated micro-focusing station for structural biology where small crystals (~ 10 μm) could be measured.

Table A. Experiments currently supported at XOR beamlines

Beamline	Capabilities
1-BM	Powder Diffraction, GISAXS Reflectivity and Surface Scattering Fuel Spray Radiography
1-ID	High-Energy Scattering – Macroscopic Stress/Strain/Texture Measurements, Microscopic Stress/Strain/Texture Measurements, Pair Distribution Function (PDF) Measurements, Diffuse Scattering, Small Angle X-ray Scattering High-Resolution Powder Diffraction Time-Resolved Powder Diffraction Phase Contrast Imaging White-Beam Experiments
2-BM	Microtomography Diffraction Imaging Microdiffraction
2-ID-B	Scanning Transmission / Fluorescence Microscopy, Coherent Scattering
2-ID-D	Scanning Fluorescence Microscopy, Micro- / Nano-Diffraction
2-ID-E	Scanning Fluorescence Microscopy
3-ID	Nuclear Resonant Scattering, High-Resolution Inelastic Scattering
4-ID-C	Spectroscopy and Scattering (XMCD) Photoemission Electron Spectroscopy (PEEM) Surface Magnetism Spectroscopy / Reflectivity in High (7 Tesla) Magnetic Field
4-ID-D	Spectroscopy / Reflectivity (XMCD) Resonant and Non-Resonant Diffraction Low-Energy Diffraction Diffraction Contrast Imaging Fluorescence Contrast Imaging Spectroscopy / Reflectivity in Medium (4 Tesla) Magnetic Field
7-ID-B	White / Pink Beam Scattering Measurements White / Pink Beam Imaging Measurements
7-ID-C	Time-Resolved Micro-Beam Scattering Surface Diffraction, COBRA
7-ID-D	Fast Laser Pump/X-ray Probe Spectroscopy
8-ID-E	Micro-Diffraction XPCS using Zone-Plate GISAXS Test-Bed for Prototype Nano-Focusing Instruments

8-ID-I	X-ray Photon Correlation Spectroscopy (XPCS) Monochromatic or Pink-Beam
9-BM-B	Spectroscopy
9-BM-C	Scattering
9-ID-B	Medium Energy Resolution Inelastic Scattering Surface Diffraction and Reflectivity Micro-Diffraction
9-ID-C	Liquid Surface Diffraction Small-Angle X-ray Scattering
11-ID-B	Magnetic Compton Scattering High-Energy Scattering - PDF Measurements Powder Diffraction Measurements, Single Crystal Diffraction
11-ID-C	High-Energy Scattering – High-Resolution Diffuse Scattering Powder Diffraction, PDF Diffraction Measurements in a 4 T Magnetic Field
11-ID-D	Time-Dependant Laser Pump-Probe Spectroscopy (100 ps) Spectroscopy (XAFS), Surface Diffraction and Reflectivity Single Crystal Diffraction
12-BM	Spectroscopy (XAFS), Surface Diffraction and Reflectivity
12-ID-B	Surface Scattering and Reflectivity, XMCD
12-ID-C	Small Angle Scattering (SAXS), Anomalous Small Angle Scattering (ASAXS) and Wide Angle Scattering (WAXS)
12-ID-D	MOCVD Chamber with Psi Goniometer for Surface Diffraction and Reflectivity, MBE Chamber with LEED and REED Capabilities X-ray Standing Waves (XSW) Optics
20-BM	Spectroscopy Diffraction Anomalous Fine Structure (DAFS) Measurements General Diffraction
20-ID-B	Micro-XAFS Micro-Fluorescence RIXS
20-ID-C	Diffraction Anomalous Fine Structure (DAFS) Measurements General Diffraction MBE Chamber and XSW Optics Time resolved (100 ps) Pump-Probe Laser XAFS Measurements

Table B. Current APS CAT capabilities

CAT	Beamline	Discipline	Supported Techniques
DND	5-BM-C	Material Science Polymer Science	-Tomography -Powder diffraction
	5-BM-D	Material Science Polymer Science	-X-ray absorption fine structure (XAFS) in situ catalysis -High energy scattering (to 65 keV) -Polymer
	5-ID	Material Science Polymer Science	-Macromolecular crystallography -Powder diffraction -Small angle x-ray scattering (SAXS) -Polymer SAXS/WAXS -Inorganic crystallography -Surface diffraction -X-ray standing waves (UHV and non-UHV)
MU	6-ID	Material Science	-Liquid scattering -Magnetic x-ray scattering -Powder diffraction -Surface diffraction -Liquid surface scattering
	6-ID-D	Material Science	-High energy x-ray scattering -Magnetic x-ray scattering -Powder diffraction -Time-resolved x-ray scattering
NE	8-BM	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
MR	10-BM 10-ID	Materials Science Material Science Environmental Science	-Deep X-ray Lithography -XAFS Microscopy -X-ray absorption fine structure (XAFS) -Diffraction anomalous fine structure (DAFS)
GSE	13-BM	Geo Science Environmental Science	-High pressure diffraction and imaging using the multi-anvil press -High pressure diffraction and spectroscopy using the diamond anvil cell (external heating) -Brillouin scattering in the diamond anvil cell -Microtomography -Surface diffraction and scattering -X-ray absorption fine structure spectroscopy

CAT	Beamline	Discipline	Supported Techniques
	13-ID	GeoScience Environmental Science	-High pressure diffraction and spectroscopy in the diamond anvil cell (laser heating) -High pressure diffraction and imaging using the multi-anvil press -Surface and interface diffraction, scattering and spectroscopy -X-ray fluorescence microprobe -X-ray absorption fine structure spectroscopy (microbeam) -Fluorescence microtomography - Inelastic scattering
CARS	14-BM-C	Life Sciences	-Macromolecular crystallography -Time-resolved x-ray scattering
	14-BM-D	Life Sciences	-Macromolecular crystallography -Micro-diffraction -Multi wavelength anomalous dispersion (MAD) -Time-resolved x-ray scattering
	14-ID	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD) -Time-resolved x-ray scattering
CARS	15-ID	Material Science Chemistry	-Anomalous and Resonant Scattering -Liquid scattering -Time-resolved x-ray scattering -Charge density scattering -Small Angle X-ray Scattering -Micro-crystallography -Liquid and Solid Surface Scattering
HP	16-ID-B	Material Science GeoScience	-X-ray absorption fine structure (XAFS) -Compton scattering -Inelastic scattering -Micro-diffraction -Nuclear Resonant Scattering -Powder diffraction -Diamond Anvil Cell (DAC)

CAT	Beamline	Discipline	Supported Techniques
	16-ID-D	Material Science GeoScience	-Nuclear Forward Scattering -Nuclear Resonant Inelastic X-ray Scattering -Inelastic X-ray Scattering -X-ray Raman Scattering -X-ray Emission Spectroscopy -Resonant Inelastic X-ray Scattering
IMCA	17-BM	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
	17-ID	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
BIO	18-ID	Life Sciences	-X-ray absorption fine structure (XAFS) -Fluorescence spectroscopy -Small angle x-ray scattering (SAXS) -Time-resolved x-ray scattering -Fiber Diffraction
SBC	19-BM	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
	19-ID	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
SER	22-ID	Life Sciences	-Macromolecular crystallography -Multi wavelength anomalous dispersion (MAD)
SGX	31-ID	Life Sciences	-Macromolecular crystallography
UNI	33-BM	Material Science	-Topography -Powder diffraction -Single crystal diffraction -General Diffraction

CAT	Beamline	Discipline	Supported Techniques
	33-ID	Material Science	-Anomalous and Resonant Scattering -Inelastic scattering -Small angle x-ray scattering (SAXS) -Surface diffraction -Ultra-small Angle X-ray Scattering -General Diffraction
	34-ID	Material Science	-Coherent x-ray scattering -Micro - diffraction -Microprobe

Table C. Future dedicated XOR beamlines

Beamline	Capabilities
1-BM	GISAXS, Reflectivity, Diffraction
1-ID	High-Energy Scattering –Stress/Strain/Texture Measurements High-Energy SAXS High-Resolution Powder Diffraction Phase Contrast Imaging
2-BM	Microtomography
2-ID	2 – 32 keV microscopy, micro/nanodiffraction
3-ID	Nuclear Resonant Inelastic Scattering (NRIXS) High-Resolution Inelastic Scattering (HERIX)
4-ID-C	0.5 keV – 3.0 keV Magnetic Spectroscopy
4-ID-D	2.6 keV – 45 keV Magnetic Spectroscopy
7-ID-B	Time-Resolved White / Pink Beam Imaging Measurements
7-ID-C	Time-Resolved Micro-Beam Scattering
7-ID-D	Fast Laser Pump / X-ray Probe Spectroscopy
8-ID-E	GISAXS
8-ID-I	X-ray Photon Correlation Spectroscopy (XPCS)
9-BM	Spectroscopy (XAFS)
9-ID-B	Liquid surface diffraction
9-ID-C	Medium Energy Resolution Inelastic X-ray Scattering (MERIX)
11-BM	Powder Diffraction
11-ID-B/C	High-Energy Powder Diffraction, PDF, and Diffuse Scattering
11-ID-D	Time-Dependant Laser Pump-Probe Spectroscopy (100 ps)
12-BM	Spectroscopy (XAFS)
12-ID-B	USAXS
12-ID-C	Small Angle X-ray Scattering (SAXS), (WAXS)
20-BM	XAFS, Diffraction Anomalous Fine Structure (DAFS) Measurements
20-ID-B	Micro-XAFS
20-ID-C	Diffraction Anomalous Fine Structure (DAFS) Measurements X-Ray Raman, surface XAFS, Laser pump / X-ray probe XAFS
26-ID	Hard-x-ray nanoprobe (20 nm) for materials science
30-ID	HERIX, NRIXS
33-BM	Topography, General purpose diffraction
33-ID	General purpose diffraction, surface science endstations
34-ID-C	Coherent diffraction imaging
34-ID-E	3D X-ray diffraction microscope
New 32-ID	phase contrast and absorption imaging, tomography, topography
New ID	2.6 keV – 45 keV magnetic scattering
New ID	0.5 keV – 3.0 keV magnetic scattering
New ID	Bio-nanoprobe hard-x-ray scanning microscopy
New ID	1 – 5 keV microscopy, ARPES, and coherent diffraction